Patent Application

of

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TWO-DIMENSIONAL ANTI-SCATTER GRID AND COLLIMATOR DESIGNS, AND ITS MOTION, FABRICATION AND ASSEMBLY

This is a continuation-in-part of U.S. Patent Application Serial No. 09 459,597, filed on December 13, 1999, the entire contents of which being expressly incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention:

The present invention relates to a method and apparatus for making focused and unfocused grids and collimators which are movable to avoid grid shadows on an imager, and which are adaptable for use in a wide range of electromagnetic radiation applications, such as x-ray and gamma-ray imaging devices and the like. More particularly, the present invention relates to a method and apparatus for making focused and unfocused grids, such as air core grids, that can be constructed with a very high aspect ratio, which is defined as the ratio between the height of each absorbing grid wall and the thickness of the absorbing grid wall, and that are capable of permitting large primary radiation transmission therethrough

Description of the Related Art:

Anti-scatter grids and collimators can be used to eliminate the scattering of radiation to unintended and undesirable directions. Radiation with wavelengths shorter than or equal to soft x-rays can penetrate materials. The radiation decay length in the material decreases as the atomic number of the grid material increases or as the wavelength of the radiation increases. These grid walls, also called the septa and lamellae, can be used to reduce scattered radiation in ultraviolet, x-ray and gamma ray systems, for example. The grids can also be used as collimators, x-ray masks, and so on.

For scatter reduction applications, the grid walls preferably should be two-dimensional to eliminate scatter from all directions. For many applications, the x-ray source is a point source close to the imager. An anti-scatter grid preferably should also be focused. Methods for fabricating and assembling focused and unfocused two-dimensional grids are described in U.S. Patent Number 5,949,850, entitled "A Method and Apparatus for Making Large Area Two-dimensional Grids", the entire content of which is incorporated herein by reference.

When an anti-scatter grid is stationary during the acquisition of the image, the shadow of the anti-scatter grid will be cast on the imager, such as film or electronic digital detector, along with the image of the object. It is undesirable to have the grid shadow show artificial patterns.

The typical solution to eliminating the non-uniform shadow of the grid is to move the grid during the exposure. The ideal anti-scatter grid with motion will produce uniform exposure on the imager in the absence of any objects being imaged.

One-dimensional grids, also known as linear grids and composed of highly absorbing strips and highly transmitting interspaces which are parallel in their longitudinal direction, can be moved in a steady manner in one direction or in an oscillatory manner in the plane of the grid in the direction perpendicular to the parallel strips of highly absorbing lamellae. For two-dimensional grids, the motion can either be in one direction or oscillatory in the plane of the grid, but the grid shape needs to be chosen based on a specific motion.

The following discussion pertains to a two-dimensional grid with regular square patterns in the x-y plane, with the grid walls lined up in the x-direction and y-direction. If the grid is moving at a uniform speed in the x-direction, the film will show unexposed stripes along the x-direction, which also repeat periodically in the y-direction. The width of the unexposed strips is the same or essentially the same as the thickness of the grid walls. This grid pattern and the associated motion are unacceptable.

If the grid is moving at a uniform speed in the plane of the grid, but at a 45 degree angle from the x-axis, the image on the film or imager is significantly improved. However, strips of slightly overexposed film parallel to the direction of the motion at the intersection of the grid walls will still be present. As the grid moves in the x-direction at a uniform speed, the grid walls block the x-rays everywhere, except at the wall intersection, for the fraction of the time

$$2d / D,$$

where d is the thickness of the grid walls and D is the periodicity of the grid walls. At the wall intersection, the grid walls blocks the x-rays for the fraction of the time

$$2d / D \leq t \leq d / D,$$

depending on the location. Thus, stripes of slightly overexposed x-ray film are produced.

Methods for attempting to eliminate the overexposed strips discussed above are disclosed in U.S. Patent Nos. 5,606,589, 5,729,585 and 5,814,235 to Pellegrino et al., the entire contents of each patent being incorporated herein by reference. These methods attempt to eliminate the overexposed strips by rotating the grid by an angle A, where $A = \operatorname{atan}(n / m)$, and m and n are integers. However, these methods are unacceptable or not ideal for many applications.

Accordingly, a need exists for a method and apparatus for eliminating the overexposed strips associated with two-dimensional focused or unfocused grid intersections.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a grid where the walls focus to a point, a grid where the walls focus to a line or an unfocused grid with parallel walls that is configured to minimize grid shadow when the grid is moved during imaging.

Another object of the present invention, therefore, is to provide a method and apparatus for manufacturing a focused or unfocused grid which is configured to minimize overexposure at its wall intersections when the grid is moved during imaging.

A further object of the present invention is to provide a method and apparatus for moving a focused or unfocused grid so that no perceptible areas of variable density are cast by the grid onto the film or other two-dimensional electronic detectors.

These and other objects of the present invention are substantially achieved by providing a grid, adaptable for use with electromagnetic energy emitting devices. The grid comprises at least one solid metal layer, formed by electroplating. The solid metal layer comprises top and bottom surfaces, and a plurality of solid integrated, intersecting walls, each of which extending from the top to bottom surface and having a plurality of side surfaces. The side surfaces of the walls are arranged to define a plurality of openings extending entirely through the layer, and at least some of the side surfaces have projections extending into respective ones of the openings. The projections can be of various shapes and sizes, and are arranged so that a total amount of wall material intersected by a line propagating in a direction, for example, along an edge of the grid, for each period along the grid is substantially the same and is also substantially the same as another total amount of wall material intersected by another line for each period

propagating in another direction substantially parallel to the edge of the grid at any distance from the edge.

These and other objects are further substantially achieved by providing a method for minimizing scattering of electromagnetic energy in an electromagnetic imaging device which is adapted to obtain an image of an object on an imager. The method includes placing a grid between an electromagnetic energy emitting source of the electromagnetic imaging device and the imager. The grid comprises at least one metal layer including top and bottom surfaces and a plurality of solid integrated, intersecting walls, each of which extending from the top to bottom surface and having a plurality of side surfaces, the side surfaces of the walls being arranged to define a plurality of openings extending entirely through the layer, and at least some of the side surface having projections extending into respective ones of the openings. The method further includes moving the grid in a grid moving pattern while the electromagnetic energy emitting source is emitting energy toward the imager.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will be more readily apprehended from the following detailed description when read in connection with the appended drawings, in which:

Fig. 1 shows a section of a focused stationary grid according to an embodiment of the present invention, in which the grid openings are focused to a point x-ray source;

Fig. 2a is a schematic of the grid shown in Fig. 1 rotated an angle of 45 degrees with respect to the x and y axes, and being positioned so that the central ray emanates from point x-ray source onto the edge of the grid;

Fig. 2b is a schematic of the grid shown in Fig. 1 rotated at an angle of 45 degrees with respect to the x and y axes, and being positioned so that the central ray emanates from point x-ray source onto the center of the grid;

Fig. 3 is an example of a top view of a grid layout as shown in Fig. 1, modified and positioned so that one set of grid walls are perpendicular to a direction of motion along the x-axis and the other set of grid walls is at an angle 0 with respect to the direction of motion, thus forming a parallelogram grid pattern applicable for linear grid motion;

Fig. 4 is an example of a top view of a grid layout as shown in Fig. 1, modified and positioned so that one set of grid walls is perpendicular to the direction of motion along the x-axis and the other set of grid walls makes an angle 0 with respect to the direction of motion, thus forming another parallelogram grid pattern applicable for linear grid motion;

Fig. 5 is an example of a top view of a grid layout as shown in Fig. 1, modified so that the angle of the grid walls are neither parallel nor perpendicular to the direction of grid motion along the x-axis, thus forming a further parallelogram grid pattern applicable for linear grid motion;

Fig. 6 is a variation of the grid pattern shown in Fig. 5, in which the grid openings are rectangular;

Fig. 7 is a variation of the grid pattern shown in Fig. 5 in which the grid openings are squares;

Fig. 8 is a variation of the grid pattern shown in Fig. 5 having modified corners at the wall intersections according to an embodiment of the present invention for eliminating artificial images or shadows on the imager along the direction of linear motion of the grid;

Fig. 9 is the top view of only the additional grid areas that were added to a square grid shown in Fig. 7 to form the grid pattern shown in Fig. 8;

Fig. 10 is the top view of a grid with modified corners at the wall intersections according to another embodiment of the present invention for eliminating artificial images or shadows on the imager along the direction of linear motion of the grid;

Fig. 11 is a top view of only the additional grid areas that were added to a square grid shown in Fig. 7 to form the grid pattern shown in Fig. 10;

Fig. 12 is a detailed view of a wall intersection of the grid illustrating a general arrangement of an additional grid area that is added to the wall intersection of the grid;

Fig. 13 is a detailed view of a wall intersection of the grid illustrating a general arrangement of an additional grid area that is added to the wall intersection of the grid;

Fig. 14 is a detailed view of a wall intersection of another grid according to an embodiment of the present invention, illustrating a general arrangement of an additional grid area that is added proximate to the wall intersection and not connected to any of the grid walls;

Fig. 15 is a detailed view of a wall intersection of another grid according to an embodiment of the present invention, illustrating a general arrangement of an additional grid area that is added to the wall intersection of the grid, such that two rectangular or substantially rectangular pieces are placed at opposing (non-adjacent) left and right corners of the wall intersection;

Fig. 16 is a detailed view of a wall intersection of another grid according to an embodiment of the present invention, illustrating a general arrangement of an additional grid area that is added to the wall intersection of the grid, such that two trapezoidal pieces are placed at opposing (non-adjacent) left and right corners of the wall intersection;

Fig. 17 shows a top view of a portion of a grid according to an embodiment of the present invention, having more than one type of modified corner as shown in Figs. 12-16;

Fig. 18 shows one layer of grid to be assembled from two sections and their joints, using the pattern as shown in Fig. 7;

Fig. 19 shows the location of the imaginary central ray and reference lines for photoresists exposures using the grid shape of Fig. 4;

Figs. 20a and 20b illustrate exemplary patterns of x-ray masks used to form the grid pattern shown in Fig. 19 according to an embodiment of the present invention;

Figs. 21a and 21b show an exposure method according to an embodiment of the present invention which uses sheet x-ray beams, such that Fig. 21a shows the cross-section in the plane of the sheet x-ray beam and Fig. 21b shows the cross-section perpendicular to the sheet x-ray beam, and the x-ray mask and the substrate are tilted with respect to the sheet x-ray beam to form the focusing effect of the grid;

Fig. 21c shows another exposure method according to an embodiment of the present invention which uses sheet x-ray beams to form the focusing effect of the grid;

Fig. 22 shows an exposure method according to an embodiment of the present invention which is used in place of the method shown in Fig. 21b for exposing grids or portions of grids where the walls, joints or holes are not focused;

Fig. 23 shows an example the top and bottom patterns of the exposed photoresists exposed according to the methods shown in Figs. 21a and 21b;

Fig. 24 shows an example of the top and bottom patterns of an incorrectly exposed photoresists which was exposed using only two masks and a sheet x-ray beam;

Figs. 25a and 25b show an example of x-ray masks used to expose the central portion of right-hand-side of a focused grid shown in Fig. 18 using a sheet x-ray beam according to an embodiment of the present invention;

Fig. 25c shows an example of an x-ray mask used to expose the grid edge joints of the right-hand-side of a focused grid for a point source shown in Fig. 18 using a sheet x-ray beam according to an embodiment of the present invention;

Fig. 26 shows a portion of the grid including the left joining edge and a wide border;

Fig. 27 shows an example of an x-ray mask used to expose the grid edge joint and the border of Fig. 26, which is in addition to the masks already shown in FIGS. 25a and 25b, according to an embodiment of the present invention;

Figs. 28a and 28b show an example of an x-ray masks used to expose the photoresist for the focused grids for a point source shown in Figs. 7, 8, 10 or 17 using a sheet x-ray beam according to an embodiment of the present invention;

Fig. 28c shows an example of an x-ray mask required to expose the additional grid structure for linear motion according to an embodiment of the present invention.

Fig. 29 is a side view of an example of a grid including a frame according to an embodiment of the present invention.

Fig. 30 illustrates a top view of the frame shown in Fig. 29, less the grid layers; and

Fig. 31 illustrates pieces of a grid layer that can be assembled in the frame shown in Figs. 29 and 30.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a method and apparatus for making large area, two-dimensional, high aspect ratio, focused or unfocused x-ray anti-scatter grids, anti-scatter grid/scintillators, x-ray filters, and the like, as well as similar methods and apparatus for ultraviolet and gamma-ray applications. Referring now to the drawings, Fig. 1 shows a schematic of a section of a two-dimensional, focused anti-scatter grid 30 produced by a method of grid manufacture according to an embodiment of the present invention, as described in more detail in U.S. Patent No. 5,949,850 referenced above.

The object to be imaged (not shown) is positioned between the x-ray source and the x-ray grid 30. The grid openings 31 which are defined by walls 32 are square in this example. However, the grid openings can be any practical shape as would be appreciated by one skilled in the methods of grid construction. The walls 32 are uniformly thick or substantially uniformly thick around each opening in this figure, but can vary in thickness as desired. The walls 32 are slanted at the same angle as the angle of the x-rays emanating from the point source, in order for the x-rays to propagate through the holes to the imager without significant loss. This angle increases for grid walls further away from the x-ray point source. In other words, an imaginary line extending from each grid wall 32 along the x-axis 40 could intersect

the x-ray point source. A similar scenario exists for the grid walls 32 along the y-axis 50.

As shown, the x-ray propagates out of a point source 61 with a conical spread 60. The x-ray imager 62, which may be an electronic detector or x-ray film, for example, is placed adjacent and parallel or substantially parallel to the bottom surface of the x-ray grid 30 with the x-ray grid between the x-ray source 61 and the x-ray imager. Typically, the top surface of the x-ray grid 30 is perpendicular or substantially perpendicular to the line 63 that extends between the x-ray source and the x-ray grid 30.

To facilitate the description below, a coordinate system in which the grid 30 is omitted will now be defined. The z-axis is line 63, which is perpendicular or substantially perpendicular to the anti-scatter grid, and intersects the point x-ray source 61. The $z = 0$ coordinate is defined as the top surface of the anti-scatter grid. As further shown, the central ray 63 propagates to the center of the grid 30, which is marked by a virtual "+" sign 64.

Figs. 2a and 2b show schematics of two air-core x-ray anti-scatter grids, such as grid 30 shown in Fig. 1, which are stacked on top of each other in a manner described in more detail below to form a grid assembly. These layers of the grid walls can achieve high aspect ratio such that they are structurally rigid. The stacked grids 30 can be moved steadily along a straight line (e.g., the x-axis 40) during imaging. As shown in these figures, the grids 30 have been oriented so that their walls extend at an angle of 45° or about 45° with respect to the x-axis 50. The top surface of the top grid 30 is in the x-y plane.

The central ray 63 from the x-ray source 61 is perpendicular or substantially perpendicular to the top surface of the top grid 30. For mammographic applications, the central ray 63 propagates to the top grid 30 next to the chest wall at the edge or close to the edge of the grid on the x-axis 40, which is marked as location 65 in Fig. 2a. For general radiology, the central ray 63 is usually at the center of the top grid 30, which is marked as location 64 in Fig. 2b. In this example, the line of motion 70 or

one set of the walls 32 (i.e., the septa) is at 45° with respect to the line of motion 70, and the shape of the grid openings 31 is nearly square. The grid assembly can move in just one direction or it can move in both directions in the x-y plane. During motion, the speed at which the grid moves should be constant or substantially constant.

Two categories of grid patterns can be used with linear grid motion to eliminate non-uniform shadow of the grid. The description below pertains to portions of the grid not at the edges of the grid, so the border is not shown. For illustration purposes only, the dimensions of the drawings are not to scale, nor have they been optimized for specific applications.

I. Grid Design Art Type I for Linear Motion

As discussed above, the present invention provides a two-dimensional grid design and a method for moving the grid so that the image taken will leave no substantial artificial images for either focused or unfocused grids for some applications. In particular, as will now be described, the present invention provides methods for constructing grid designs that do not have square patterns. The rules of construction for these grids are discussed below.

Essentially, Type 1 methods for eliminating grid shadows produced by the intersection of the grid walls are based on the assumptions that: (1) there is image blurring during the conversion of x-rays to visible photons or to electrical charge; and/or (2) the resolution of the imaging device is low. A general method of grid design provides a grid pattern that is periodic in both parallel and perpendicular (or substantially parallel and perpendicular) directions to the direction of motion. The construction rules for the different grid variations are discussed below.

Grid Design Variation I.1: A Set of Parallel Grid Walls
Perpendicular to the Line of Motion

Fig. 3 shows a top view of an exemplary grid layout that can be employed in a

perpendicular or substantially perpendicular to the direction of motion. and a set of grid walls. B. intersecting A. The thicknesses of grid walls A and B are a and b. respectively. The thicknesses a and b are equal in this figure. but they are not required to be equal. The angle θ is defined as the angle of the grid wall B with respect to the x-axis. The grid moves in the x-direction as indicated by 70. P_x and P_y are the periodicities of the intercepting grid wall pattern in the x- and y-directions. respectively. D_x and D_y represent the pitch of grid cells in the x- and y-directions. respectively.

The periodicity of the grid pattern in the x-direction is $P_x = MD_x$. where M is a positive integer greater than 1. The periodicity of the grid pattern in the y-direction is $P_y = M(D_y / N)$. where N is a positive integer greater than or equal to 1. $M \neq N$ and $P_y = |\tan(\theta)| P_x$. For linear motion. the grid pattern can be generated given D_x. (θ or D_y). (M or P_x) and (N or P_y). The parameter range for the angle θ is $0° < |\theta| < 90°$. The best values for the angle θ are away from the two end limits. 0° and 90°. The grid intersections are spaced at intervals of P_y / M in the y-direction.

If D_x. θ. M and N are given. the parameters P_x. P_y. and D_y can be calculated Figure 3 is a plot of a section of the grid for the following chosen parameters: $\theta = 45°$. $M = 3$ and $N = 1$.

If the parameters D_x. D_y. M and N are chosen. the angle θ. P_x and P_y can be calculated: $P_x = MD_x$. $P_y = ND_y$ and $\theta = \pm \operatorname{atan}(P_y / P_x)$. Figure 4 is a plot of a section of the grid for the parameters $N = 2$. $M = 7$ and $\theta = \operatorname{atan}(2D_y / 7D_x)$.

Grid Design Variation I.2: Grid Walls Not Perpendicular to the Line of Motion

Figure 5 is the top view of a section of the grid layout where neither grid walls A nor B are perpendicular to the direction of linear motion. The thicknesses of grid walls A and B are a and b. respectively. The thicknesses a and b are equal in this figure. but they are not required to be equal. The angle...

relative to the x-axis are ϕ and 0, respectively. Choosing D, (M or P_y), (N or P), and angles (0 or D) and ϕ, then $P = \tan(0)P$, $N = P/D$ and ($M = P/D$). The centers of grid intersections are separated by a distance $P \cdot M$ in the y-direction. Fig. 5 shows an example where $0 = -15°$, $\phi = -80°$, $M = 5$ and $N = 1$.

Fig. 6 is the top view of a section of the grid layout where neither grid walls A or B are perpendicular to the direction of motion, but grid wall A is perpendicular to grid wall B, thus a special case of Fig 5, where the grid openings are rectangular. The thicknesses of grid walls A and B are a and b, respectively. The thicknesses are equal in this figure, but again, they are not required to be equal. The angles between the grid walls A and B relative to the x-axis are ϕ and 0, respectively. By choosing D, (M or P_y), (N or D_y), (0 or P) and ϕ, then $P_x = |\tan(0)|P$, $P = ND$, and $P_y = MD_y$. The centers of grid intersections are separated by a distance $P \cdot M$ in the y-direction. Fig. 6 shows an example where $0 = 10°$, $\phi = -80°$, $M = 10$ and $N = 1$.

Comments on the Grid Motion Associated with Grid Design I

For all grid layout methods, the range of parameters for the grid can vary depending on many factors, such as film versus digital detectors, the type of phosphor used in film, the type of application, and whether there is direct x-ray conversion or indirect x-ray conversion, etc. The ultimate criteria are that the overexposed strip caused by grid intersections is close enough to each other so that they do not appear in the imaging system.

Some general conditions can be given for the range of parameters for Grid Design Type I and associated motion. It is better for grid openings to be greater than the grid wall thicknesses a and b. For film, $P \cdot M$ should be smaller than the x-ray to optical radiation conversion blurring effect produced by the phosphor. For digital imagers with direct x-ray conversion, it is preferable that pixel pitch in the y-direction is an integer multiple of the spacing, $P \cdot M$. Otherwise, the grid shadows will be

The distance of linear travel, L, of the grid during the exposure should be many times the distance P_λ, where $kP_x > L > (kP_x - \delta L)$, $D_x > \delta L > a \sin(\varphi)$, $D_y > \delta L > b \sin(\theta)$, $\delta L / P_x << 1$, $k >> 1$, and k is an integer. The ratio of $\delta L / L$ should be small to minimize the effect of shadows caused by the start and stop. The distance L can be traversed in a steady motion in one direction if it is not too long to affect the transmission of primary radiation. Assuming that the x-ray beam is uniform over time, the speed the grid traverses the distance L should be constant, but the direction can change. In general, the speed at which the grid moves should be proportional to the power of the x-ray source. If the distance L to be traveled in any one direction at the desired speed is too long, causing reduction of primary radiation, then it can be traversed by steady linear motion that reverses direction.

II. Grid Design Type II for Linear Motion

The present invention provides other two-dimensional grid designs and methods of moving the grid such that the x-ray image will have no overexposed strips at the intersection of the grid walls A and B. The principle is based on adding additional cross-sectional areas to the grid to adjust for the increase of the primary radiation caused by the overlapping of the grid walls. This grid design and construction provides uniform x-ray exposure.

Two illustrations of the concept are given below, followed by the generalized construction rules. This grid design is feasible for the SLIGA fabrication method described in U. S. Patent 5,949,850 referenced above, because x-ray lithography is accurate to a fraction of a micron even for a thick photoresist.

Grid Design Variation II.1: Square Grid Shape
with an Additional Square Piece

Fig. 7 shows a section of a square patterned grid with uniform grid wall thickness a and b rotated at a 45° angle with respect to the direction of motion. When square pieces in the shape of the septa intersection are added to the grid next to the

shadow for a grid moving with linear motion 70. In the Fig. 8, $D' = D = P = P'$ and $\theta = 45°$. The additional grid area is shown alone in Fig. 9.

Grid Design Variation II.2: Square Grid Shape with Two Additional Triangular Pieces

Fig. 10 shows another grid pattern, which has the same or essentially the same effect as the grid pattern in Fig. 8, by placing two additional triangular pieces at opposite sides of intersecting grid walls. In this Fig. 10 example, $D = D = P = P'$ and $\theta = 45°$. The additional grid area is shown alone in Fig. 11.

With these modified corners added to the grid, there will not be any artificial patterns as the grid is moved in a straight line as indicated by 70 for a distance L, where $kD > L \geq (kD - \delta L)$, $D >> \delta L > s$, $\delta L << L$, $k >> 1$ and k is an integer. Along the x-axis, the grid wall thickness is s and the periodicity of the grid is $P = D$. The distance of linear travel L should be as large as it can be while keeping the maximum transmission of primary radiation. The condition for linear grid motion in just one direction is easier for grid Design Type II to achieve than grid Design Type I or the designs in U.S. Patents by Pellegrino et al., because $P > D$ for grid Design Type I.

General Construction Methods for Quadrilateral Grid Design Type II for Linear Motion

The exact technique for eliminating the effect of slight overexposure caused by the intersection of the grid walls with linear motion is to add additional grid area at each corner. Two special examples are shown in Figs. 8 and 10 discussed above, and the general concept is described below and illustrated in Figs. 12-16. The general rule is that the overlapping grid region C formed by grid walls A and B has to be "added back" to the grid intersecting region, so that the total amount of the wall material of the grid intersected by a line propagating along the x-direction remains constant at any point along the x-axis. In other words, the total amount of wall material intersected

intersected by a line propagating in a direction parallel to the x-axis along the edge of a grid of the type shown, for example, in Figs. 8 or 10, is identical to the amount of wall material of the grid intersected by a line propagating in a direction parallel to the x-axis through any position, for example, the center of the grid.

This concept can be applied to any grid layout that is constructed with intersecting grid walls A and B. The widths of the intersecting grid walls do not have to be the same and the intersections do not have to be at 90°, but grid lines cannot be parallel to the x-axis. The width of the parallel walls B do not have to be identical to each other, nor do they need to be equidistant from one another, but they do have to be periodic along the x-axis with period P_x. The widths of the parallel lines A do not have to be identical to each other, nor do they need to be equidistant from one another, but they do have to be periodic along the y-axis with period P_y.

The generalized construction rules are described using a single intersecting corner of walls A and B for illustration as shown in Figs. 12-16. The top and bottom corners of parallelogram C are both designated as γ and the right and left corners of the parallelogram C as $\beta1$ and $\beta2$, respectively. Dashed lines, f, parallel to the x-axis, the direction of motion, are placed through points γ. The points where the dashed lines f intersect the edges of the grid lines are designated as $\alpha1$, $\alpha2$, $\alpha3$ and $\alpha4$.

Fig. 12 shows the addition to the grid in the form of a parallelogram F formed by three predefined points: $\alpha1$, $\alpha2$, $\beta1$, and δ, where δ is the fourth corner. This is the construction method used for the grid pattern shown in Fig. 8.

Fig. 13 shows the addition of the grid area in the shape of two triangles, E1 and E2, formed by connecting the points $\alpha1$, $\alpha2$, $\beta1$ and $\alpha3$, $\alpha4$, $\beta2$, respectively. This is the construction method used to make the grid pattern shown in Fig. 10.

There are an unlimited variety of shapes that would produce uniform exposure for linear motion. Samples of three other alternatives are shown in Figs. 14-16. They produce uniform exposure because they satisfy the criteria that the lengths through the grid in the x-direction for any value y are identical. There is no or essentially no difference in performance of the grids if motion is implemented correctly. Additional

when steady linear motion is implemented. Fig. 17, for example, illustrates and arrangement where different combinations of grid corners are implemented in one grid. However, the choice of grid corners depends on the ease of implementation and practicality. Also, since it is desirable for the transmission of primary radiation to be as large as possible, the grid walls occupy only a small percentage of the cross-sectional area.

General Construction Methods for Grid Design Type II for Linear Grid Motion

It should be first noted that this concept does not limit grid openings to quadrilaterals. Rather, the grid opening shapes could be a wide range of shapes, as long as they are periodic in both x and y directions. The grid wall intercepts do not have to be defined by four straight line segments. Artificial non-uniform shadow will not be introduced as long as the length of the lines through the grid in the x-direction are identical through any y coordinate. In addition to adding the corner pieces, the width of some sections of the grid walls would have to be adjusted for generalized grid openings.

However, not every grid shape that is combined with steady linear motion produces uniform exposure without artificial images. The desirable grid patterns that produce uniform exposure have to satisfy, at a minimum, the following criteria:

- The grid pattern has to be periodic in the direction of motion with periodicity P_y.

- No segment of the grid wall is primarily along the direction of the grid motion.

- The grid walls block the x-ray everywhere for the same fraction of the time per spatial period P at any position perpendicular to the direction of motion.

- The grid walls do not have to have the same thickness.

- The grid patterns are not limited to quadrilaterals.

- These grid patterns have to be coupled with a steady linear motion such that the distance of the grid motion, L, satisfies the condition described in Sections Grid Design Type I and Type II for Linear Motion.

- If the walls are not continuous at the intersection or not identical in thickness through the intersection, the construction rule that must be maintained is that the length of the line through the grid in the x-direction is identical through any y-coordinate. Hexagons with modified corners are examples in this category.

Implementation of the Grid Design Type II for Linear Grid Motion

The additional grid area at the grid wall intersections can be implemented in a number of ways for focused or unfocused grids to obtain uniform exposure. The discussion will use Figs. 8 and 10 as examples.

1. The grid patterns with the additional grid area, such as Figs. 8, 10, 17, and so on, may have approximately the same cross-sectional pattern along the z-axis.

2. Since the additional pieces of the grid are for the adjustment of the primary radiation, these additional grid areas in Figs. 8, 10, 17, and so on, only have to be high enough to block the primary radiation. This allows new alternatives in implementation.

   - A portion of the grid layer need to have the additional grid area, while the rest of the grid layer do not. For example, a layer of the grid is made with pattern shown in Fig. 8, while the other layers can have the pattern shown in Fig. 7.

   - The portion of the grid with the shapes shown in Figs. 8, 10, 17, and so on, can be released from the substrate for assembly or attached to a low atomic weight substrate.

   - The portion of the grid with the pattern shown in Figs. 8, 10, 17, and

example, these layers can be made of higher atomic weight materials, while the rest of the grid can be made from fast electroplating material such as nickel. The high atomic weight material allows these parts to be thinner than if nickel were used. For gold, the height of the grid can be 20 to 50 μm for mammographic applications. The height of the additional grid areas depends on the x-ray energy, the grid material, the application and the tolerances for the transmission of primary radiation.

- The photoresist can be left in the grid openings to provide structure support, with little adverse impact on the transmission of primary radiation.

3. The additional grid areas shown in Figs. 9, 11, and so on, can be fabricated separately from the rest of the grid.

- These areas can be fabricated on a low atomic weight substrate and remain attached to the substrate.

- These areas can be fabricated along with the assembly posts, which are exemplified in Figs. 16a and 16b of U.S. Patent Number 5,949,850, referenced above.

- Patterns shown in Figs. 9, 11, and so on, can be made of a material different from the rest of the grid. For example, these layers can be made from materials with higher atomic weight, while the rest of the grid can be made of nickel. The high atomic weight material allows these parts to be thinner than if nickel were used. For gold, the height of the grid can be 20 to 100 μm for mammographic applications. The height of the additional grid areas depends on the x-ray energy, the grid material, the application and the tolerances for the transmission of primary radiation.

- The photoresist can be left on for low atomic weight substrate to provide structure support with little adverse impact on the transmission of primary radiation.

Grid Parameters and Design

Examples of the parameter range for mammography application and definitions are given below. Grid Pitch is P. Aspect Ratio is the ratio between the height of the absorbing grid wall and the thickness of the absorbing grid wall. Grid Ratio is the ratio between the height of the absorbing wall including all layers and the distance between the absorbing walls.

	Range	Best case
Grid Type	Type I or II	Type II FIG. 10
Grid Opening Shape	Quadrilateral	Square
Thickness of Absorbing Wall on the top plane of the grid	10 μm 200 μm	≈ 20-30 μm
Grid Pitch for Type I	1000 μm 5000 μm	
Grid Pitch for Type II	100 μm 2000 μm	≈ 300-1000 μm
Aspect Ratio for a Layer	1 – 100	> 15
Number of Layers	2 – 100	2 – 7
Grid Ratio	3 – 10	5-8

However, it should be noted that different parameter ranges are used for different applications, and for different radiation wavelengths.

III. Grid Joint Design

Designs of grid joints were described in U.S. Patent Number 5,949,850, referenced. Fig. 18 shows a grid to be assembled from two sections, using the pattern of Fig. 7 as an example. The curved corner interlocks in the shape of 110 and 111 shown in FIG. 18 are found to be more desirable structurally than other grid joints. The details of the corner can vary depending on the implementation of the additional grid structure with motion. Straight line boundaries are also acceptable as long as they retain their relative alignments.

IV. Grid Fabrication

Unfocused grids of any design can be easily fabricated with one mask and a sheet x-ray beam.

When grid size is too large to be made in one piece, sections of grid parts can be made and assembled from a collection of grid pieces. Grids with high grid ratios can be obtained by stacking if they cannot be made the desired thickness in one layer.

Focused grids of any pattern can be fabricated by the method described in U.S. Patent Number 5,949,850, referenced above. For focused grids for point source, methods for exposing the photoresist using a sheet of parallel x-ray beams are described below.

Grid Design Type I For Linear Motion and Single Piece

If the pattern of the grid in the x-y plane can be made in one piece (not including the border and other assembly parts), the easiest method is to expose the photoresist twice with two masks. The pattern of Fig. 4 is used as an example to assist in the explanation below. This method can be applied to any grid patterns with quadrilateral shapes formed by two intersecting sets of parallel lines.

1. For exemplary purposes, the case where the central ray is located at the center of the grid, as shown in Fig. 19, which is marked by a virtual "+" sign 100, will be considered. Two imaginary reference lines 101 are drawn running through the "+" sign, parallel to grid walls A and B.

2. The grid pattern is to be produced by two separate masks. The desired patterns for the two masks are shown in Fig. 20a and 20b.

3. The photoresist exposure procedure by the sheet x-ray beam is shown in Figs. 21a and 21b. For the first exposure, an x-ray mask 730, with pattern shown in Fig. 20a or 20b, is placed on top of the photoresist 710 and properly aligned, as follows. In Fig. 21a, the sheet x-ray beam 700 is oriented in the same plane as the paper, and the reference lines 101 in Figs. 20a or 20b of the x-ray masks 730 are parallel to the sheet x-ray beam 700. In Fig. 21b, the sheet x-ray beam 700 is oriented perpendicular to the plane of the paper, as are the reference lines of x-ray mask 730. The x-ray mask 730, photoresist 710, and substrate

the line 740 that connects the virtual "·" sign 100 with the virtual point x-ray source 62 is perpendicular to the photoresist 710. The angle α is 0° when the reference line 101 is in the plane of the x-ray source 700. To obtain the focusing effect in the photoresist 710 by the sheet x-ray beam 700, the assembly 750 rotates around the virtual point x-ray source 62 in a circular arc 760. This method will produce focused grids with opening that are focused to a virtual point above the substrate.

There are situations that one would like to produce a layer of the grid with that are focused to a virtual point below the substrate as shown in Fig. 21c. In Fig. 21c, the sheet x-ray beam 700 is oriented perpendicular to the plane of the paper, as are the reference lines of x-ray mask 730. The assembly 750 is positioned in such a way that the line 740 that connects the virtual "·" sign 100 with the virtual point x-ray source 62 is perpendicular to the photoresist 710. The angle α is 0° when the reference line 101 is in the plane of the x-ray source 700. To obtain the focusing effect in the photoresist 710 by the sheet x-ray beam 700, the assembly 750 rotates around the virtual point x-ray source 62 in a circular arc 770.

4. For the second exposure, the second x-ray mask is properly aligned with the photoresist 710 and the substrate 720. The exposure method is the same as in FIGS. 21a and 21b or 21c.

5. To facilitate assembly, a border is desirable. The border can be part of Figs. 20a or 20b; or it can use a third mask. The grid border mask should be aligned with the photoresist 710 and its exposure consists of moving the assembly 750 such that the sheet x-ray beam 700 always remains perpendicular to the photoresist 710, as shown in Fig. 22. The assembly 750 moves along a direction 780.

6. The rest of the fabrication steps are the same as in described in U.S. Patent No. 5,949,850, referenced above.

Grid Design Type I For Linear Motion and Multiple Pieces Joint Together per Layer

If two or more pieces of the grid are required to make a large grid, the grid exposure becomes more complicated. In that case, at least three masks will be required to obtain precise alignment of grid pieces.

The desired exposure of the photoresist is shown in Fig. 23, using pattern 115 shown on the right-hand-side of Fig. 18 as an example. The effect of the exposure on the photoresist outside the dashed lines 202 is not shown. The desirable exposure patterns are the black lines 120 for one surface of the photoresist, and are the dotted lines 130 for the other surface. The location of the central x-ray is marked by the virtual "+" sign at 200. The shape of the left border is preserved and all locations of the grid wall are exposed.

Although the procedures discussed above with regard to Figs. 21a and 21b are generally sufficient to obtain the correct exposure near the grid joint using two masks, one for wall A and one for wall B, incorrect exposure may occur from time to time. This problem is illustrated in Fig. 24. The masks are made so as to obtain correct photoresist exposure at the surface of the photoresist next to the mask. The dotted lines 130 denote the pattern of the exposure on the other surface of the photoresist. Some portions of the photoresist will not be exposed 140, but other portions that are exposed 141 should not be. The effect of the exposure on the photoresist outside the dashed lines 202 is not shown.

At least three x-ray masks are required to alleviate this problem and obtain the correct exposure. Each edge joint boundary needs a mask of its own. These are shown in Figs. 25a-25c. Fig. 25a shows a portion of the grid lines B as lines 150, which do not extend all the way to the grid joint boundary on the left. Fig. 25b shows a portion of the grid lines A as items 160, which do not extend all the way to the grid joint boundary on the left. Fig. 25c shows the mask for the grid joint boundary on the left. The virtual "·" 200 shows the location of the central ray 63 in Figs. 25a-25c. The distances from the joint border to be covered by each mask depend on the grid dimensions, the intended grid height and the grid

The exposures of the photoresist 710 by all three masks shown in FIGS. 25a-25c follow the method described above with regard to Figs. 21a and 21b or Figs. 21a and 21c. The three masks have to be exposed sequentially after aligning each mask with the photoresist.

If this pattern is next to the border of the grid as shown in Fig. 26, then the grid boundary 180 can be part of the mask of the grid joint boundary on the left, as shown in Fig. 27. At a minimum, the grid border 180 consists of a wide grid border for structural support, may also include patterned outside edge for packaging, interlocks and peg holes for assembly and stacking. The procedure would be to expose the photoresist 710 by masks shown in Figs. 25a and 25b following the method described in Figs. 21a and 21b or Figs. 21a and 21c. The exposure of the joint boundary section 170 in Fig. 27 follows the method described in Figs. 21a and 21b or Figs. 21a and 21c while the exposure of the grid border section 180 in Fig. 27 follows the method described in Fig. 22.

Grid Design Type II For Linear Motion

The exposure of the photoresist for a "tall" type II grid pattern design for linear grid motion, such as those grid patterns illustrated in Figs. 8, 10, 17, and so on, can be implemented based on the methods described in U. S. Patent Number 5,949,850, referenced above. The grid is considered "tall" when

$$H \sin(\Phi_{max}) \gg s \ .$$

where H is the height of a single layer of the grid, Φ_{max} is the maximum angle for a grid as shown in Figs. 2 and 3, and s is related to the thickness of the grid wall as shown in Figs. 7, 8, 10 and 17. "High" grids are not easy to expose using long sheet x-ray beams when the same grid pattern is implement from top to bottom on the grid.

As described in an earlier section, the grid shape shown in Figs. 8, 10, 17, and so on, need only be just high enough to block the primary radiation without causing undesirable exposure. Using the grid pattern shown in Fig. 10 as an example, three x-ray masks, Figs. 28a, 28b and 28c can be used for the exposure. Additional x-ray

for the joints and borders would be the same as for that describing Fig. 27. The virtual "·" 210 shows the location of the central ray 63 in Figs. 28a, 28b and 28c. The dashed lines 211 denote the reference line used in the exposure of the photoresist by sheet x-ray beam as described in Figs. 21a and 21b or Figs. 21a and 21c. The three masks have to be exposed sequentially after aligning each mask with the photoresist.

V. Packaging

The grids have to be assembled, and sealed for protection and made rigid for sturdiness, as will now be described.

1. Assembly: A layer of the grid can be made in one piece or assembled together using a number of pieces and stacking the layers using pegs, as described in U.S. Patent Number 5,949,850, referenced above.

2. Sturdiness: The grid can be made rigid when two or more layers become physically attached after stacking to make a higher grid. A few of these methods are described below.

   - The grid and pegs can be soldered together along the outer border.

   - A layer of the grid, made of lead/tin, can be placed next to a layer of the grid made of a different material such as nickel. When heated, these two layers will be attached. This process can be repeated until the desired height is reached for the grid.

   - A layer of the grid does not have to be electroplated using just one type of material. For example, either the top or bottom surface, or both surfaces, of a predominantly nickel grid layer can be electroplated with lead tin next to the nickel before it is polished to the desirable height. When layers of grids made by this approach are stacked together and heated, the various layers become physically connected. This method does not coat the whole grid with solder.

- Many parts of an assembled and stacked nickel grid will be fused together when the grid is brought up near the annealing temperature.

3. Framed Construction: Instead of using pegs and fixed posts, a thick and wide frame can be sued for assembly and packaging. Fig. 29 is a side view of the grid showing frame 400. The bottom layer 401 of the grid has extra material at corners of the intersections of its walls as shown, for example, in Figs. 8, 10 and 17, to provide uniform exposure during grid motion, and the other grid layers 402 do not have extra material at the corners of their wall intersections.

   The frame 400 can be made by the SLIGA process as known in the art. Fig. 30 illustrates a top view of an exemplary frame 400. The shape of the frame wall can be any design appropriate for interlocking, and the material of which the frame is made can be any suitable material, as long as it is not excessively soft. Also, the frame 400 can be made by joining two or more pieces together.

   The grid is assembled by fitting grid layers 401 and 402 into the frame. If grid layer 401 is attached to the substrate but the photoresist is removed, the frame 400 can be fitted over grid layer 401, and the grid layers 402 can then be fit into the frame. Since the frame 400 provides structural support and alignment of the openings in the grid layers 400 and 401, the joints of the grid pieces as shown in Fig. 31 can be relaxed to straight borders 110 and 111, and do not need to be rounded as shown in Fig. 18, for example.

4. Sealing: To protect the assembled grid, the grid has to be covered and sealed using low atomic number materials. There are a wide variety of commercially available choices for sealing material.

Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without

from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims.